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PHYSICAL SIMULATION OF LAND VEHICLES WITH OBSTACLE AVOIDANCE AND VARIOUS TERRAIN INTERACTIONS

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Topics : motion control - physically based modeling - driving simulator - real time animation and simulation.

I. Introduction

The work presented here is a contribution to a robotic project which involves a complete system for the teleprogramming of an autonomous planetary rover. We are mainly concerned in this system by the optimisation and the assessment of robust trajectories for the autonomous rover. More generally the problem is how to plan the motions for a complex articulated land vehicle moving in a natural environment. Geometric and dynamic aspects will have to be considered in this problem.

During the ten past years, robotic researchers have mainly focused on the problem of planning the motions for a robot. Most of the research has dealt with path planning, i.e. the problem of finding collision-free trajectories between two given configurations of the robot.

Because of the intrinsic complexity of motion planning, many researchers have solved a subset of the problem using purely geometric approaches. Despite a great ability to solve geometrical problems, the effective generation of viable paths for a robot having numerous DOF's and moving in a natural environment is beyond the capabilities of existing geometrical reasoning based implementations.

More recent results have been obtained in the field of motion planning. They involve planning methods dealing with non integrable kinematic constraints such as non-holonomic constraints [BarLat 90] [FLL 90]. Others methods deal with trajectory optimisations under kinematic constraints [BarLL 90]. These methods cannot be efficiently applied in our motion planning problem which concerns a complex robot moving in a natural and little known environment : in this situation, the physical interactions existing between the vehicle and the ground are of prime

importance because frictions, slidings, skids and grip phenomena can influence the robot motion.
The work we have contributed to is based on a new method for solving motion planning problems in the case of a natural environment containing both obstacles that can be crossed over by the vehicle and obstacles that have to be avoided.
The method involves adapted tools to model and to simulate the dynamic aspects of the problem. A physical simulation of the task performance provides an additional prediction tool of the robot's behaviour.
The use of physical models means that the geometric models of the ground and of the vehicle must first be converted into appropriate representations. It also led us to combine the physical simulation and the motion planning capabilities through two complementary concepts : the concept of "generalised obstacles" and the concept of "physical target".
Beyond the motion planning application, these concepts have led us towards a pertinent means of controlling the motions in a dynamic simulation.

II. Tools for physical modelisation and simulation

II.1 The Physical Modeler-Simulator Cordis-Anima

The physical model does not describe movement, but what generates it, i.e. the physical object itself. Thus, with a physical representation, movement results from a set of actions applied onto the simulated object. The displacements and deformations of the simulated object are related to the actions by the laws of physics.

We can thus characterize a real physical object, or a simulated physical object, by a dipole combining the two dual variables : the extensive ones, positions, and the intensive ones, forces (figure 1).

$$O(\vec{P}, \vec{F}) = 0$$

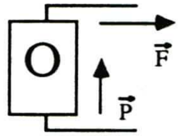


Figure 1 : Characterization of a physical object.

Since 1978 the Acroe team has carried out expert evaluations and implementations to design and to build a complete Modeler-Simulator for physical objects : the Cordis-Anima system [Flo 78-91, Cad 79-90 Luc 90-91, Jim 89-90].
These analyses have led to the definition of the basic functions for a modeler-simulator derived from physical modeling. It must enable operator gestural control. The modelisation and simulation processes must be real-time oriented.

The two major constraints are :
• Modularity : the operator must be able to build all kinds of objects and scenes, with various non linear interactions and discontinuities.
• Experimentability : the relationship between the model to simulate and the simulation algorithms themselves must run as quickly as possible in order to achieve numerous simulation tests to adjust the models and, at the same time, to produce valid simulations.

These constraints cannot be achieved by any kind of models. We have conducted a consistent analysis of the model-types proposed by Physics and the Engineering Sciences, to extract a principle adapted to this modeler-simulator approach. This led us to the choice of the continuous lumped constant model .
When the objects are too complex or too little known, prior structural discretisation is carried out, thus breaking down them into components, each being described by differential equation systems relating the two dual variables Force and Position (or speed). In fact, the constants localisation principle introduces the notion of "component", and it can be regarded as a language, i.e. as a representation that gives rise to object creation by assembling components.
Furthermore, natural phenomena are extremely non-linear, such as border phenomena (collisions and contacts), or material transformations (agglutination, plasticity). These cannot be represented in an equational form and require state sequencing representation. The latter can be achieved by this "components formalism" in which some components are linear and others non-linear .
With this model type a system of interacting objects is represented by a discrete network (figure 2). The nodes represent the material components (punctual masses), and the links represent interactions between these components.

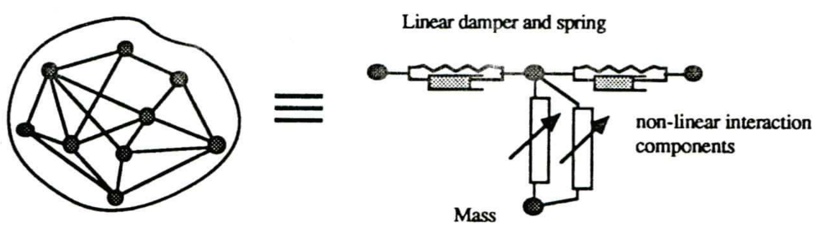


Figure 2 : the general lumped constant model.

A simulation algorithm corresponds to each element (nodes and links). It computes a specific dynamic function. To each link, we associate a quadripole which computes the forces as a function of the positions of the two connected masses. The calculation is made according to a specific interaction law :

$$\vec{F_1} = - \vec{F_2} = \Phi\ (\vec{P_1}, \vec{P_2})$$

When we have obtained these forces, for each mass, a dipole computes the new position according to the Newtonian laws :

$$\sum \vec{F} = M.\vec{\Gamma} = M . \frac{d^2\vec{P}}{d\,t^2}$$

This model type is mainly oriented towards the explicit representation of the interactions which are generated by physical objects. For example, it is adapted to predict the influence of the environment upon the motions effectively produced by a vehicle.

II.2 Models for the environment and for the robot

In our problems the physical objects to be considered are the ground or obstacles to be crossed over, the obstacles to avoid, and the functional components of the vehicle.
The ground data are more often available as CAD models with either additional information, or hypothesis about the sort of ground the vehicle has to move over (it could be sand, mud, stones, etc ...). This means that the geometrical models of the ground have first to be converted into appropriate representations. We must achieve a physical representation for the ground under the form of a set of punctual masses with associated non penetration areas. We have called those components (mass + non penetration area) the "balls", they allow the representation of pieces of matter in the form of 'agglomerates' [Jim 89, Luc 91].
CAD models only convey information about the ground topology. But we need, for the physical simulation, a texture model for the robot-ground interactions. This involves additional informations about the kind of terrain, and, in fact, about the kind of interactions the vehicle is liable to encounter.
We have developed a set of interaction types, like elastic and viscous interactions, dry friction or grip-like interaction (notching phenomena), and intermolecular links. The commutation between different interactions laws allows us to represent complex composed interactions such as interactions composed of grip and viscous laws.
In addition, physical models of the vehicle have to exist in the form of a library of various complexity level models which is elaborated by an expert designer using the Cordis-Anima Modeler-Simulator. In this way, the discrete physical models of several vehicle types such as tracked vehicles, wheeled vehicles and vehicles with several articulations have been constructed and tested with the Modeler-Simulator (see § IV).

II.3 Operator control and gestural perception

In a dynamic system, wherever the signals (force/position couples for instance) are detected, these signals are dependent on the global state of the object. Suppose we model an object by means of a set of masses, spring-damper and non-linear interactions, and we put this object in interaction with an environment also represented by a discrete network. Finally, suppose we run the simulation of the whole system. In this instance the simulated system can be represented in each point (the masses for instance) as a dipole, whose impedance is that of the whole system yielded to this point. If this point is chosen as a manipulation point, the operator can have physical informations about the global physical behavior of the whole system. This means that

if the object is jammed, the operator will sense the jammings and their global magnitude. In a complementary way, visualisation can localize the jammed points.
Thus the operator can visually and 'energetically' apply an efficient control of the object motions. This 'external control' provides natural and optimum driving conditions.

The entire network defined at the required complexity level is made up of (figure 3) :

- the robot model : it is composed of the models of all the functionnal components (locomotion system, general morphology, inertia distribution ..)
- the ground model : It is an approximation of the terrain topology : hollows, hills, rocks...
- an interaction model : it is a physical model of the interactions between the vehicle and the ground. This model depends on the kind of ground (mud, sand, hard ground, stones ...) and on the locomotion means (wheels, tracks, legs ...)

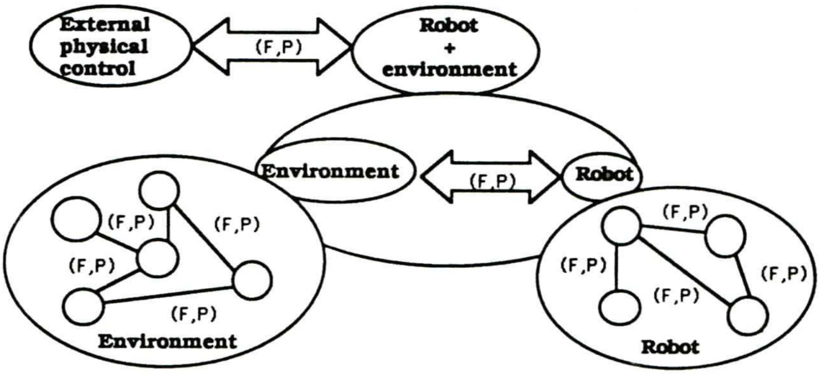


figure 3 : robot-environment model and operator control.

III. Integration of geometrical knowledge and planning step instructions

We have therefore adopt the idea of inserting a physical simulator into a motion planning robotic line. This is to test the consistency of produced solutions from a dynamic point of view. Consequently, we have developed some concepts and their associated tools to design and to implement an interface between the different information levels; that of the robotic line, i.e. logical and geometrical models with symbolic representation of the action, and that of the physical simulation : physical structures, evolution of dynamic systems.

III.1 Obstacle avoidance by physical modeling : Generalised Obstacles

Classically, a natural terrain is composed by two categories of obstacles :

- avoidable - and more often, to avoid - obstacles, for which an avoidance strategy is applied.
- unavoidable obstacles, that is to say those where contacts are unavoidable, which are generally not considered, like the ground for example. They are of prime importance, particularly for locomotion in a natural environment. We have to reintroduce the effects produced by those obstacles on the motion within the physical simulation.

We have defined the notion of "Generalised Obstacles" that embraces in the same notion the two categories. The idea of obstacle itself is therefore broadened by this notion : the obstacle, that is a nuisance to avoid, becomes a object that can guide motions.

To do this, we transform the obstacle avoidance problem (which is a complex geometric problem) into a problem of using obstacles as guides for motions. The latter is easier to solve when choosing physical models. We will thus have only one generic problem to solve, which is the physical interaction between physical moving objects.
In order to fully grasp the generalised obtacles function, let us consider the way the human being, and in fact every living being, deals with obstacle avoidance. We can think about the following anticipation metaphor : everything happens as though the danger processing organ sees objects bigger than they really are. They seem surrounded by a survival area built from the experience of real collisions. We replace, by learning, the visible physical outline of objects by a virtual one which characterizes the safety distance to maintain between the objects and our body. This virtual envelop is a materialized model of anticipation reflexes.
Similarly we will replace every obstacle to be avoided within the simulation, by a virtual protective one used as an anticipator and as a guide for the motions (and of course as a collision avoider with the real obstacle). The distance between real and virtual obstacles depend on path narrowness and hazards.

Notice that those anticipators are adaptative. The virtual obstacles are physical objects with inertia, and whose dynamic behaviour is computed. Thus, they are supposed to move with the vehicle motions, and adapt themselves to the situation (figure 4).

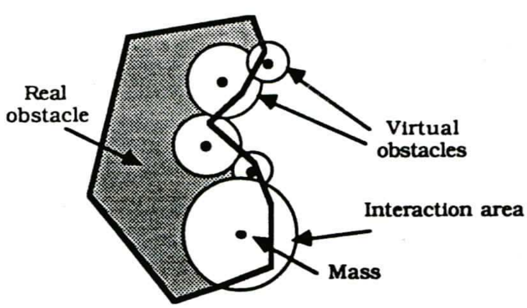


Figure 4 : "generalised obstacles"

The definition of generalised obstacle allows the physical simulation to take into account constraints like safety margins. The real obstacles are localised from the CAD model. Notice that approximative position and shape are sufficient to define the generalised obstacle. Generalised obstacles can either be interactively placed by an operator or automatically defined according to criteria concerning the real obstacles and safety margins.

The principle can be carried further : a trajectory, such as channel or polygonal path, could also be directly treated as a physical object, and as such, be materialized by a virtual physical envelop working like the generalised obstacles and its purpose would be to impose more or less tight trajectory tracking (see Key-situation 4 and chronogram 1).

III.2 Introducing planning data in a physical world ; the "physical target"

Targets are usually means to convey control and strategic instructions. They can be outputs of planning stages, describing for example subgoal layouts and progression strategies, such as "step back to be able to pass". These strategies are related to intelligent behaviour and cannot be fulfilled by physical systems.

The question is then to introduce these non-physical planning data into a physical world. The chosen method is to give a physical model of these non physical data. As any physical model, this one has two correlated components : a physical object and physical interactions between this object and the vehicle. This model (object and interactions) have to be designed according to the nature of the planning targets (for example, successives target-configurations for a robot).

In this way, the notion called "the physical target" materializes strategic and tactic orders. As they are physical, the physical targets can be movable and bear temporal sequences of orders, like those describing some manoeuvres.

As a physical elementary Cordis-Anima object, the elementary physical target is a punctual mass, and the elementary interactions are attraction and non-linear visco-elastic interaction. With these elementary components, we can represent a simple attractive goal for the rover (see key-situation 6, §IV). We can force the vehicle to attain a determined spatial objective where we have located the punctual physical target, and this with some parameters to adjust such as spatial goal achievement speed and accuracy (figure 5).

In this way, we obtain the optimal practicable trajectory to attain the goal according to the dynamics of the physical scene (rover in interaction with the ground) and the obstacles avoidance.

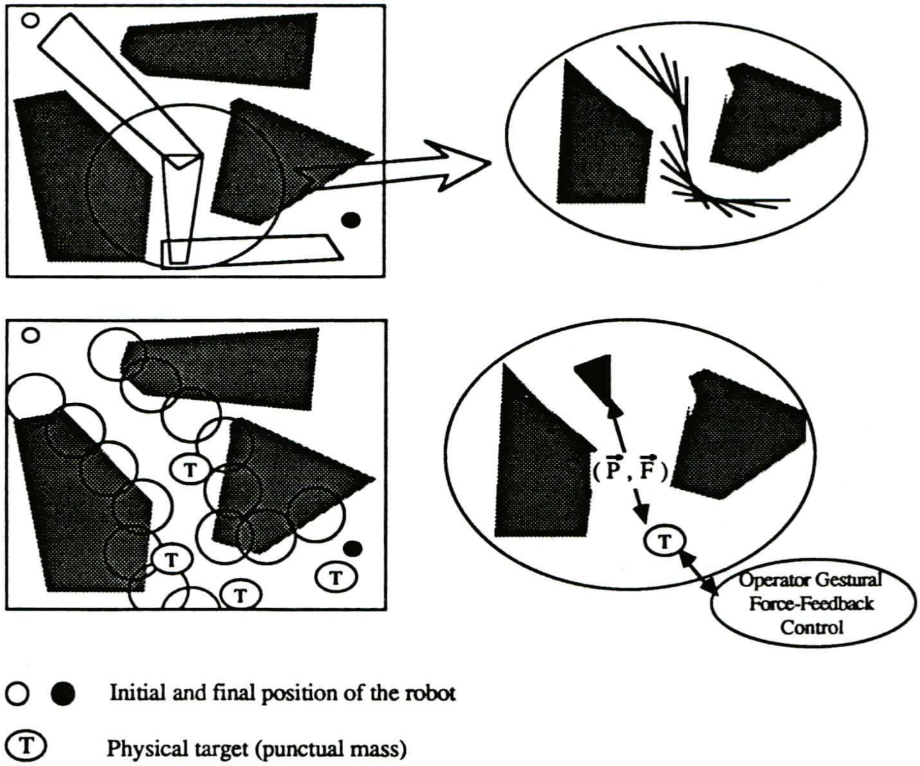


Figure 5 : spatial goal and manoeuvre : geometric and symbolic reasoning and physical world solutions

This punctual physical target can be placed by the operator or can be given by the planning process. Several targets can be combined, by specifying a set of weighted interactions between themselves and the rover. This allows to define complex strategies such as the balance between the local and the global level in the planning process.

Because they are physical, physical targets can move in the same way than the rover, and then, they can be used to directly drive the vehicle for manoeuvring or to estimate local modification of the strategy in real time. In such cases, it seems useful to have a gestural control device that enables physical feedback, because a simple 3D mouse can not give a faithfull reproduction of the decisive physical parameters. The gestural force feedback devices developed by the Acroe [Cad 84-90] allow this kind of gestural control on simulated physical objects.

III.3 Conclusion

The simulation of dynamics provides assessment of the robustness of trajectory plans coming from the motion planning system, with obstacle avoidance and motion guides. Operator direct control of the physical targets can then be viewed as an ergonomic way of testing some variations on the given solution. It is obvious that the physical simulation can only provide predictions about the possible routes for the vehicle.
The prediction efficiency then depends on operator expert evaluations as well as on his ability to exploit the visual and gestural informations accessible from the simulation.
The models flexibility and constructivity, the on-line and real time simulation (experimentability) make the Cordis-Anima Modeler Simulator a complete tool to define efficient task prediction models.

IV. Examples and Simulations

The Cordis-Anima system, with its real time simulator, its real time graphic station and its feedback gestural transducers provide multi-modal information about the simulation performance (figure 6).

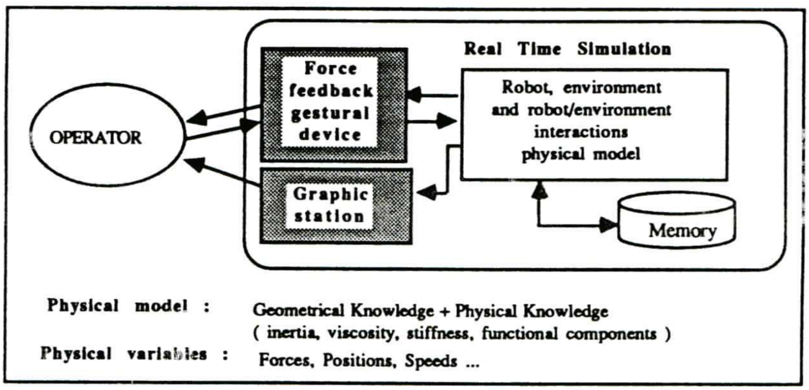


Figure 6 : The system : simulation and man/machine communication

The prediction informations produced by the simulation are available in different forms.
First, we have talk about the real time visualisation, which is performed by an Evans & Sutherland PS350 graphic station, and about the operator control by mean of the high performance force feedback devices developed by the Acroe. These represent the available information in line, i.e. during the simulation progress. The simulation also carries out the whole scenario of the dynamic evolution of the system. The operator can access the successive states of the simulated system, which is the notion of a dynamic photo. A dynamic photo

contains for each time step, the positions, the speeds and the accelerations of each material component, but also the constraints ratio of each interaction link. By analysing these signals we can assess the different variations on motions produced. Assessments are carried out according to criteria like 'safety', 'required energy', 'accuracy', 'speed' etc ... The curves achieved by simulation can then be compared with those elaborated by the robotic experts.

We have experimented some key-situations with the Cordis-Anima Modeler Simulator. These key-situations combine different elements (kind of vehicles, kind of ground, kind of interaction) and the two major concepts defined in this paper : the generalised obstacles and the physical target. The models for the vehicles, for the surfaces, and for the vehicle-ground interactions have been designed and experimented on the Cordis-Anima workstation.

The implemented models of vehicles are :
- a 2D articulated vehicule, a 2D tracked articulated vehicule, a flat vehicule with a great number of articulations.
- a 3D complex articulated rover.

The implemented models of ground are :
- a frontal view of the terrain composed by rigid and fixed obstacles.
- a frontal view of the terrain with deformation : moving rigid obstacles, great number of rigid obstacles to represent stone stacks.
- a plane view of the terrain with rigid obstacles offering restricted passages.
- a 3D hilly surface.

The physical interaction laws implemented permit :
- to cross over underneath (ground-type) obstacles according to non penetrability and friction parameters.
- to avoid lateral obstacles according to physical safety margins.

KEY - SITUATION 1 :

2D Frontal view
2D articulated vehicule
Underneath rigid obstacles

Vehicle : The simulation shows a very simplified articulated three wheel vehicle. The three wheels are represented by punctual masses with associated non-penetration areas. When the vehicle moves forward, the wheels slide over the ground (figure 7).

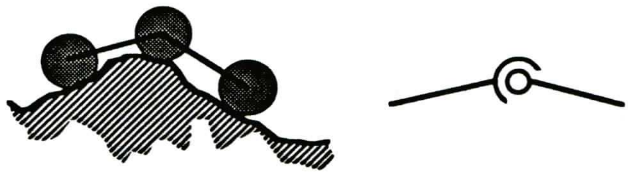


Figure 7 - Articulated vehicle getting over rigid obstacles

Environment : This is a 2D indeformable ground with obstacles to cross over. There are obstacles of different shapes and sizes. The physical model of the ground is a set of different sized "balls".

Vehicle-Ground Interaction : The interactions between the wheels and the ground is a non penetrability visco-elastic interaction.

Locomotion : The locomotion of the vehicle is provided by a fixed physical target working like a winch.

KEY - SITUATION 2 :

2D frontal view
2D tracked articulated vehicle
Underneath rigid obstacles

Vehicle : The caterpillar track is composed of several punctual masses connected by springs and dampers in a chapelet form. This string of masses is braced around an articulated body whose structure is the same as above (figure 8).

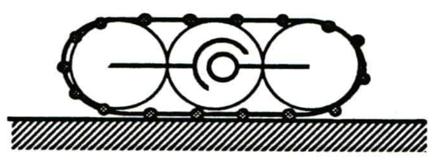


Figure 8 - Tracked vehicle

The simulation shows the difference with the previous example in real time, particularily the capacity of the track to filter obstacles (figure 9).

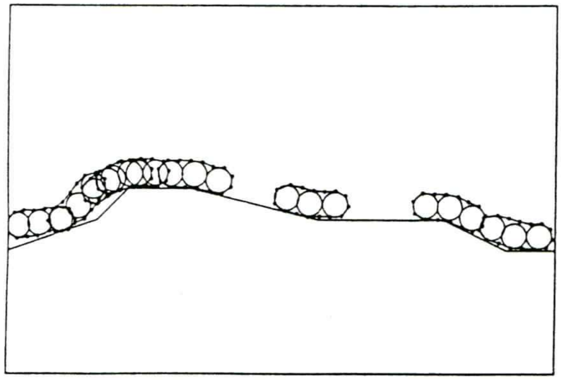


Figure 9 - Tracked vehicle getting over rigid obstacles

Environment : 2D hilly ground (obtained as above) strewn with several punctual masses. The whole scene looks like a trammel. It creates grip phenomena with the tracked vehicle.

Vehicle-Ground interaction : Interaction is similar that in the previous one but it is applied between each mass fixed on the ground and each mass of the caterpillar track.

Locomotion : As above.

KEY - SITUATION 3 :

2D frontal view
2D articulated vehicule
Underneath deformable obstacles.

The vehicule is the same as in key-situation 1.

The ground is composed by several rigid obstacles that can move. A sand-like ground simulation is obtained when each rigid obstacle is a small element physically linked with others by a physical cohesion law. They can thus constitute stacks and agglomerates. When the vehicle crosses over the stacks, they give way beneath the weight of the vehicle.

KEY - SITUATION 4 :

2D plane view
Flat train-like vehicle
Obstacle avoidance and fixed physical target

Vehicle : It is composed of low deformable elements organised and articulated like a train. This model is a first approach to a robot with many DOFs such as these used in nuclear installations (figure 10).

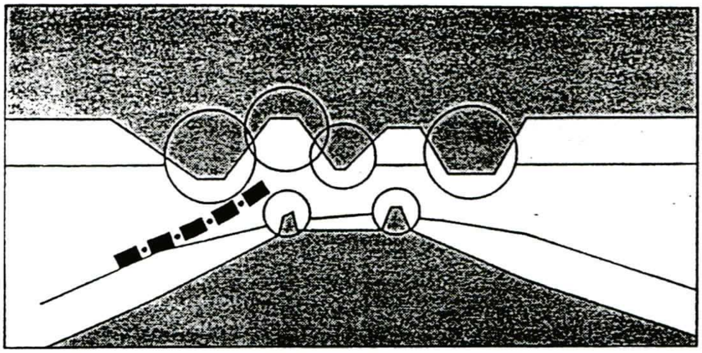


Figure 10 - train-like vehicule and obstacle avoidance

Environment : It contains real obstacles to avoid (grey tint polygones on figure 10) embedded in added virtual obstacles which implement the notion of generalised obstacles (white spheres on figure 10). We suppose that a practicable trajectory exists between the real obstacles. This trajectory is materialized by the protective generalised obstacles which are less or more penetrable.

Vehicle - Ground interaction : In this situation, there is no contact between the vehicle and the real ground. The vehicle only interact with the virtual surrounding obstacles. The interaction between the two is a visco-elastic non-penetration area with the presence of non-linearities (contacts are not permanent).

Locomotion : The locomotion is obtained in the same way as in previous tests, i.e. with fixed winch-target. But in this case, unlike the other examples, the position of the target is determinant. Here the target is experimentally placed after several attempts (as the simulation run in real time, attemps take only few seconds) until it allows the vehicle to edge its way into the restricted passage.

KEY - SITUATION 5 :

3D terrain with obstacles
3D complex martian rover
Non-penetrability and friction interaction

Vehicule : The rover is a complex 3D articulated vehicle with many DOF's (figure 11). The vehicle has six independent cone shaped wheels composed of punctual masses. The axes are assembled onto an articulated subframe. This vehicle is able to cross over fairly high obstacles. During the obstacle clearing, the subframe articulates itself and, in this way, adapts itself to the shape of the ground (see chronograms 2 and 3 on page 18).

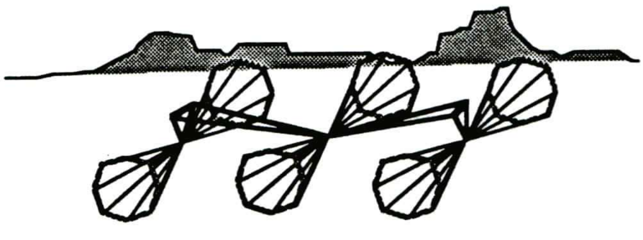
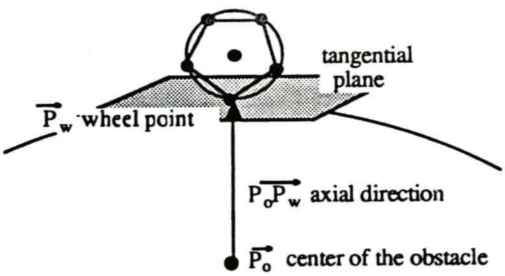


Figure 11 - 3D martian rover

Environment : Level ground with some obstacles to cross over. The obstacles are discretised by non-penetrable different sized spheres ("balls") according to the the spatial bandwith of the terrain.

Vehicle-Ground interaction : There are two kind of interactions between the masses composing the wheels, and the ground or the obstacles. The first one is the classic non-penetration law which give rigid object properties to the obstacles. The second is needed to obtain slide-free rolling motions for the wheels, unlike in key-situation 2 which used a trammel-type law. Here we define sliding friction forces that drive the wheels. These forces are proportional to the tangential speed.
In our case, the tangential speed is obtained by projecting the relative speed between the wheel point and the spherical obstacle onto the tangent plane situated at the contact point (see the figure 12).



$$\vec{V} = \overrightarrow{V_{axial}} + \overrightarrow{V_{tangent}}$$

$$\overrightarrow{V_{axial}} = \vec{V} \cdot \frac{\overrightarrow{P_oP_w}}{\left\| \overrightarrow{P_oP_w} \right\|} \quad \text{(scalar product)}$$

Interaction Law :

$$\text{if } \left\| \overrightarrow{P_oP_w} \right\| < \text{Threshold} \quad \text{then } \vec{F} = Z \, . \, \overrightarrow{V_{tangent}}$$

$$\text{else } \vec{F} = 0$$

Figure 12 - Sliding Friction Force.

Locomotion : In this simulation the "martian rover" is still winched by a fixed physical target.

KEY - SITUATION 6 :

Moving physical target
Operator force feedback control
Obstacle avoidance and on-line manoeuvre

The models for the vehicle, for the environment and for the vehicle-ground interactions are the same as in key-situation 3. The vehicle is complex and in addition, the practicable channel is more windy and cramped than in previous cases. It does't seem possible to find an optimal path for the vehicle with the use of fixed targets. We have thus used a more adaptive control.
Here the locomotion is provided by a movable target interactively moved by the operator using a gestural device. The better case is when this device is a force feedback device. The operator can thus more easely tow the vehicle through the windy passage. Because of the retroaction force, the operator feels the possible jams of the vehicle and instantaneously adapts his control.
In this example, we implement both the notion of materialization of a progression strategy and the force feedback motion control for the vehicle by means of a physical target (see chronogram 1 and the photo on page 17).

V. Conclusion

We have used lumped constant physical models to make effective motion predictions for many DOF's robotic vehicles moving in natural environments. Beyond the inherent difficulties in the design of the models themselves, we have tackled the problems of representation within the physical simulation of symbolic and strategic orders needed for motion control. The Cordis-Anima Modeler-Simulator for physical objects, initially devoted to animated images synthesis and man machine communication problems has allowed us to model and to simulate differents robotic key-situations.
The concepts of generalised obstacles and of physical target constitute effective solutions to the problem of integrating symbolic information and beyond this, to the general problem of controlling motions when working with physical models.
Our futur work has three axes. First we will aim at making the models of the vehicles more realistic by increasing the level of detail and by modeling actuators and sensors.
This goes along with a research work on physical target roles. For example, they can work as a servo-control, by applying a particular command law to some vehicle control points.
We have also to define some methods to represent realistic terrain surfaces, i.e. to be able to convert the numerical and CAD models (e.g. face-edge-vertex representations) from real measurementof the grounds into physical models.
This work is related to physics, engeenering, automation and programming sciences, it can be viewed as a first step towards a 'physical porgramming' of robotic systems.

Acknowledgement
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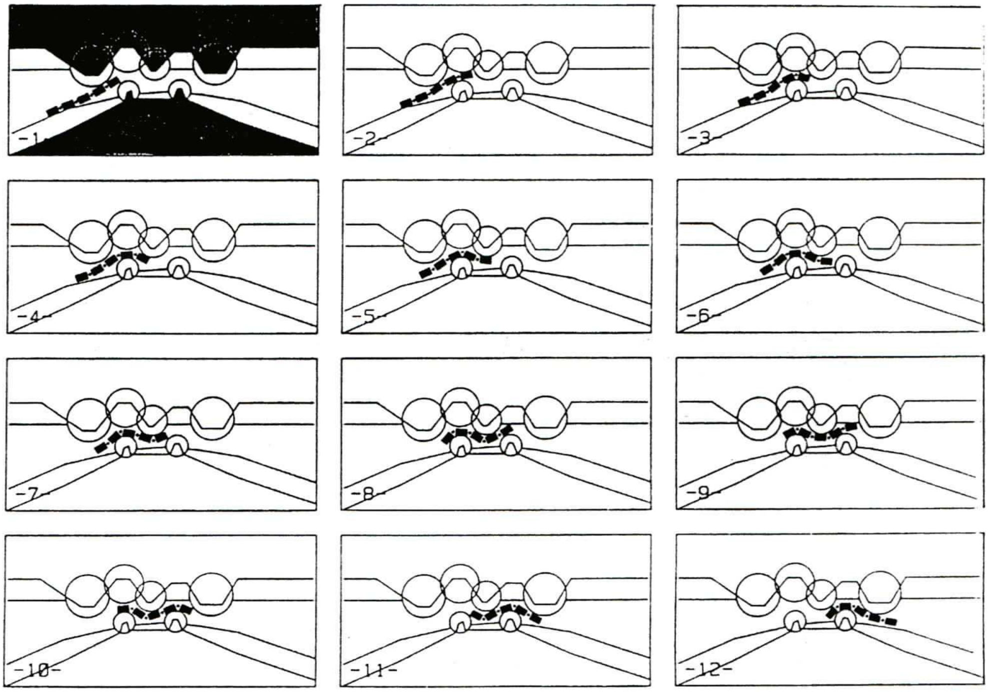
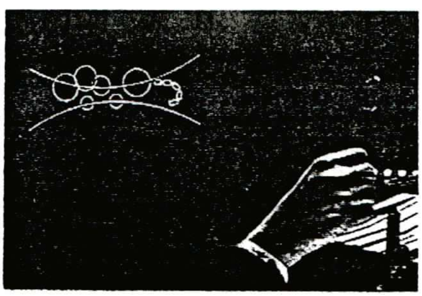
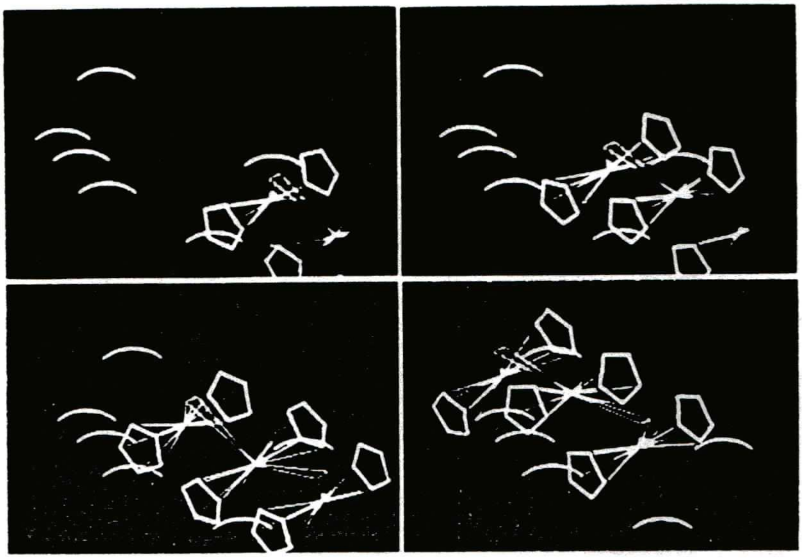


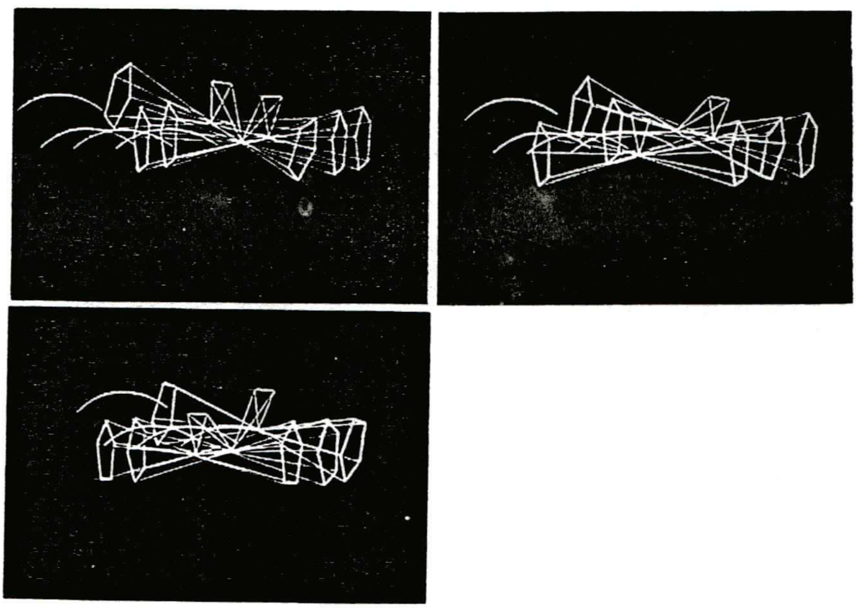
Chronogram 1 : flat articulated system. The real obstacles are in grey.



Gestural motion control with a force-feedback device.



Chronogram 2



Chronogram 3

Chronogram 2 and 3 : The 3D martian rover getting over rigid obstacles.